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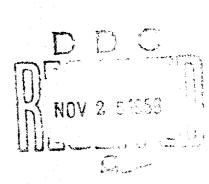
A Computer Program to Analyze Optical Parametric Up-Conversion Processes in Nonlinear Crystals

R. A. ANDREWS

Quantum Optics Branch
Optical Sciences Division

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MAVAL RESEARCH LABORATORY
Weshington, D.C.

ABSTRACT

A Fortran computer program has been developed which analyzes a nonlinear material to determine (a) the range of IR wavelengths that can be converted in a phase matched (PM) process, (b) the PM orientation of the wave vectors for critical and noncritical PM, (c) the angular aperture for PM conversion, and (d) the maximum number of resolvable lines for image conversion. These characteristics are determined as a function of IR wavelength for a given pump wavelength, pump radiation divergence, and length of nonlinear crystal.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem N01-14 Project XF-52545002-8063

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A COMPUTER PROGRAM TO ANALYZE OPTICAL PARAMETRIC UP-CONVERSION PROCESSES IN NONLINEAR CRYSTALS

INTRODUCTION

Infrared (IR) light can be up-converted to visible light, via a parametric process, in crystals which have a nonlinear susceptibility (1-3). In the second-order processes considered here, IR light of frequency ω_{IR} is mixed with intense light of frequency ω_P , called the pump light. The result is signal light of frequency $\omega_S = \omega_{IR} + \omega_P$. For the process to be efficient, the crystal must be transparent at the three frequencies involved, and momentum must be conserved; i.e., the process must be "phase matched" (PM). A process is PM if the directions of propagation in the nonlinear crystal for the three frequencies of light can be found such that the signal wave vector equals the sum of the pump and IR wave vectors, i.e., $(k_P + k_{IR}) - k_S = 0$.

Given a nonlinear crystal, it is necessary to find the range of IR wavelengths that can be up-converted in the material and to find the characteristics of the up-conversion process as a function of the IR wavelength. Up-conversion of IR to the visible necessitates the use of an intense source of laser light as a pump whose wavelength is near the long-wavelength edge of the visible spectrum. Once the wavelength of the pump source has been specified, the range of ω_{IR} for PM up-conversion can be determined. Then for each set of frequencies ω_P , ω_{IR} , and ω_S , the orientation of the crystal with respect to the wave vectors that gives a PM up-conversion, i.e., the phase match angles, can be found. In each case the wave vectors can be sither collinear or noncollinear, and both situations must be considered. Also, if the IR to be up-converted carries spatial information such as an image, one must determine such things as the acceptable angular aperture for PM up-conversion, the resolution limit* for the beam divergence of a given pump, and the orientation which maximizes the angular aperture. Further, all of the characteristics of a PM up-conversion process must be calculated as a function of ω_{IR} , the IR frequency.

Finding the PM angles and other characteristics of an up-conversion process means solving transcendental equations. To obtain any desired accuracy the complete analysis is best done on a computer using an iteration technique. This report describes a Fortran IV program which does that analysis. The characteristics of the nonlinear crystal necessary for the analysis are its limits of transparency and its refractive indexes as a function of wavelength.

The next section describes the mathematical basis of the calculation. This is followed by a description of the program itself and two appendixes which give a listing of the program, sample input data, and the corresponding output.

MATHEMATICAL FORMULATION

The requirements for PM up-conversion (4) are

$$\omega_P + \omega_{IR} = \omega_S \tag{1}$$

and

^{*}The resolution limit considered here is the particular case of an extreme multimode pump source with the IR image and pump source optically at infinity with respect to the nonlinear crystal. See, for example, "IR Image Optical Parametric Up-Conversion," R.A. Andrews, IEEE J. Quant. Electr., Jan. 1970.

$$k_P + k_{IR} = k_S , \qquad (2)$$

where the subscripts P, IR, and S refer to pump, infrared, and signal, respectively, and k is the corresponding wave vector. For a crystal of length L, PM up-conversion takes place as long as

$$\Delta k = |\Delta k| = |k_P + k_{IR} - k_S| \le \frac{2\pi}{L}, \qquad (3)$$

where for convenience we assume that Δk is measured along the direction of k_S as shown in Fig. 1. In general, the orientation of the nonlinear crystal for PM up-conversion is given by the solution to the following equation:

$$\Delta k = \left[\frac{n^i(\omega_P, \theta_P)}{\lambda_P} + \frac{n^j(\omega_{IR}, \theta_{IR})}{\lambda_{IR}} \cos \phi \right] \sec \rho - \frac{n^k(\omega_S, \theta_S)}{\lambda_S} = 0 , \qquad (4)$$

Where

 ϕ = angle between k_P and k_{IR}

 $\rho =$ angle between k_P and k_S

 θ_{ℓ} = angle between the Z-axis and $k_{\ell}(\ell = P, IR, S)$

i, j, k = 0 or E for extraordinary or ordinary polarization

It is assumed that the parametric process is confined to the yz plane, where x, y, and z are the optical axes of the nonlinear crystal, and z is the optical axis for a uniaxial crystal. However, the crystal may be optically biaxial; therefore

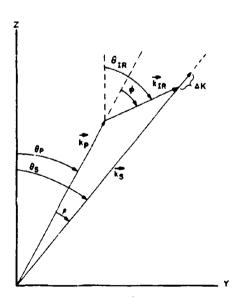


Fig. 1 - Crystal geometry for up-conversion from infrared to visible wavelengths

$$n^{O}(\omega,\theta) = n_{x}(\omega) \tag{5}$$

and

$$n^{\mathcal{B}}(\omega,\theta) = \left\{ \frac{\sin^2\theta}{\left[n_y(\omega)\right]^2} + \frac{\cos^2\theta}{\left[n_g(\omega)\right]^2} \right\}^{-1/2}.$$
 (6)

where n_x , n_y , and n_z are the refractive indexes for light polarized along the x, y, and z directions.

Solutions to Eq. (4) and, in particular, collinear up-conversion ($\phi = \rho = 0$) represent examples of critical phase matching. The noncritical phase matching (NCPM) solution (Ref. f) requires that

$$\left[\partial \Delta k (\theta_{P}, \phi) / \partial \phi\right]_{\theta_{P}} = 0 \tag{7}$$

The crystal has finite length L and up-conversion will take place whenever $\Delta k < 2\pi/L$. Hence, for a fixed pump beam direction, there will be a range of values of ϕ for which IR light will be up-converted. This range defines the angular aperture α for k_{IR} and is defined by all values of ϕ such that for a fixed value of θ_F ,

$$\Delta k (\phi, \theta_P) \leq 2\pi/L \tag{8}$$

or

$$\alpha = |\phi_1 - \phi_2| . \tag{9}$$

where

$$\begin{aligned} |\Delta k(\phi_1, \theta_P)| &= 2\pi/L , & \phi_1 > \phi_0 \\ |\Delta k(\phi_2, \theta_P)| &= 2\pi/L , & \phi_2 < \phi_0 \\ \Delta k(\phi_0, \theta_P) &= 0 . \end{aligned}$$

 α_{INT} is the angular aperture inside the crystal. Outside the crystal,

$$\alpha_{EX} = \left[\sin^{-1} \left[n^{j} (\omega_{IR}, \theta_{P} + \phi_{1}) \sin \phi_{1} \right] - \sin^{-1} \left[n^{j} (\omega_{IR}, \theta_{P} + \phi_{2}) \sin \phi_{2} \right] \right]$$
 (10)

In this manner, each PM process can be characterized by the width of the $\Delta k(\phi)$ vs ϕ curve with θ_P fixed. Hence, the half-widths are defined as

$$HW_1 = \phi_0 - \phi_1 \tag{11}$$

and

$$HW_2 = \phi_0 - \phi_2 \tag{12}$$

The pump radiation always has a finite divergence, and hence the PM angles are not well defined. Variations in θ_P will give PM up-conversion for different values of ϕ ; hence the angular aperture is increased. The divergence Δ of the pump radiation inside the crystal is, however, less than that outside, i.e.,

$$\Delta_{IMT} = \Delta_{EX}/\pi(\omega_P) . \tag{13}$$

where \bar{n} is some average index of refraction.

The maximum angular aperture is obtained with NCPM. The aperture is the greatest if, in this case, Eqs. (4) and (7) are solved with $\Delta k = -2\pi/L$. This technique is discussed by Warner. However, a larger angular aperture does not always guarantee better resolution. To determine resolution, one must find the change in ϕ that will cause a variation in θ_S just equal to the width of θ_S values caused by the divergence of the pump radiation. A variation in θ_P due to a divergence of Δ causes a change in θ_S of

$$y = \Delta + \sin^{-1}\left[\frac{k_{IR}}{k_{S}}\sin(\phi - \Delta)\right] - \sin^{-1}\left[\frac{k_{IR}}{k_{S}}\sin\phi\right]. \tag{14}$$

This change in θ_S is equivalently produced by a change in ϕ (with θ_P fixed) of

$$\epsilon = \sin^{-1}\left\{\frac{k_S}{k_{IR}}\sin\left[\Delta + \sin^{-1}\left(-\frac{k_{IR}}{k_S}\sin\Delta\right)\right]\right\}$$
 (15)

Hence, the number of resolvable lines of IR is equal to

$$R = \alpha_{INT}/\epsilon \tag{16}$$

GENERAL DESCRIPTION OF THE PROGRAM

The program is written in Fortran IV language and, in the form given in Appendix A, has been run on a CDC 3800 computer. Input to the program is minimal and is on punched cards.

Lor each material to be analyzed, it is first necessary to fit dispersion data to a Sellmeier equation of the form

$$n_i^2 = A_i + B_i/(C_i - \lambda^2) - D_i \lambda^2$$
, $(i = x, y, z)$. (17)

(The program can easily be modified to use any other dispersion relation by modifying the function FIN (W, I), which is given in Table 1.) Besides the constants A_i , B_i , C_i , and D_i , it is necessary to supply the upper and lower wavelength limits of the transparent region of the crystal, the length of the crystal, and the range of values of the pump-source divergence to be considered. This information is given on a set of four data cards for each material. The required format is given in Table 2. The first data card gives the number of materials to be analyzed. Data cards 2 through 5 are repeated for each material. The symbols used for the data are defined in Table 3.

Pump wavelengths of $0.6943~\mu$ and $1.06~\mu$ have been selected, since they lie in or near the red part of the spectrum as discussed above, and intense laser sources are readily available at these wavelengths. The program analyzes up-conversion processes in which all three wavelengths lie in the region of transparency. The IR wavelength is scanned from the lower wavelength limit of transparency upward in equal increments on a logarithmic scale. The interval is determined in statement 10 of the main program.

Table 1 Subprograms

		y
Name	Calculations	Line No. of Accuracy Test
FNX (XX, PP, DD)	Angle between kp and z-axis for PM where	222
i	$XX = angle between k_P and k_{IR}$	·
	PP = (see text)	
	DD = value of Δk at PM (see text)	
TNCPM (TCL, D)	Noncritical PM angle	144
:	TCL = collinear PM angle	1
	$D = value of \Delta k$ at PM	1
PVAR (T, P, DD, E)	Variation in ϕ for PM when θ_p is varied	178
	$T, P = PM$ angles θ_P, ϕ]
1	DD = amount θ_P is increased	
	$E = value of \Delta k$	
FDK (T, P)	Δk T,P = PM angles θ_P , ϕ	_
HWDK (L, T, P, I)	Width of Δk(φ) vs φ curve	281
	L = length of crystal	
	T, P = PM angles	
	I = index to specify type of variation in φ to be performed	
OUT	Printout routine	-
FIN (W, I)	Refractive index	_
	W = wavelength of desired index	
	I = 1, 2, or 3 corresponding to x, y, or z optical axis	
FN1 (A) FN2 (A)	Refractive index for arbitrary direction of propagation	-
FN3 (A)	A = angle between direction of propagation and r axis	
FN2C (Q) FN3C (Q)	Refractive index squared for arbitrary direction of propagation	-
	Q = same as A in FN1 (A)	

Table 2 Input Data Cards

Nata Card Number	Format	Symbols	
1	(12)	N	
2	(A5, 5X, 6F 10.1)	ANAME, UL, LL, L, DL, DU, DD	
3	(4F 10.4)	AX, BX, CX, DX	
4	(4F 10.4)	AY, BY, CY, DY	
5	(4F 10.4)	AZ, BZ, CZ, DZ	

Table 3
Definitions of Symbols

Symbol	Definition	Units
N	Number of materials to be analyzed	Integer
ANAME	Name of material	
UL, LL	Upper and lower wavelength limits for transparency	Angstrom
L	Length of crystal	Centimeter
AX, BX, DZ	Parameters for Sellmeier equation for indexes corresponding to x , y , and z optical axes. (For uniaxial crystal $z \rightarrow extraordinary polarization, x = y \rightarrow ordinary polarization.)$	

For each set of possible wavelengths, all polarization combinations are checked for a possible PM process. The output is labeled "O + O = E," etc. for (ordinary polarization) + (ordinary polarization) = (extraordinary polarization), etc. "Not Phasematchable" is printed if an orientation cannot be found for phase-matched up-conversion. If up-conversion at a given set of wavelengths is phase matchable, then all the parameters discussed in the previous section are calculated and printed (see Appendix B).

The functions of the various subprograms are listed in Table 1. In particular, the function FNX (X, P, D) is more general than need be for this program. FNX will calculate a PM angle for any orientation of k_{IR} with respect to k_P . In this case P is the angle between the $(k_P, z$ -axis) plane and the $(k_{IR}, z$ -axis) plane, and X is the angle between k_P and k_{IR} .

The various calculations are iterated until a predetermined accuracy is reached. The line numbers for the appropriate accuracy determining points in the program are listed in Table 1.

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- 3. Miller, R.C., and Nordland, W.A., IEEE J. Quant. Electr. QE-3:642 (1967)
- 4. Yariv, A., "Quantum Electronics," New York: Wiley, 1967
- 5. Warner, J., "Opto-Electronics" 1:25 (Feb. 1969)

Appendix A

PROGRAM LISTING

PROGRAM LISTING	
PROGRAM PHASMCH	00000100
DATA (UP=57.2957795) + (DN=+C17453293) + (CC=6+28318E8) + (C1=1000+)	00000200
COMMON/1/W1: W2: W3 /7/IN3/8/IN2/9/IN1/4/IX/IO/PNC	
1/11/K.TCL.TNCL.HWC1.HWC2.HWNC1.HWNC3.HWC3.HWC4.HWNC3.HWNC4.HWNC4.D.J.DI	
2/12/EXHW1.EXHW2.EXW1.EXW2.EXHW5.EXHW6.FNL1.FNL2.PC1.PNC1.PC2	000000500
3 /5/HW1+HW2+E/1"/AX+BX+CX+DX+AY+BY+CY+DY+AZ+BZ+CZ+DZ/2/K1	00000600
4 /6/NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3	00000700
REAL LL. L. KI	00000800
REAL NX1.0X2.0X3.0Y1.0Y2.0Y3.0Z1.0Z2.0Z3	00000900
READ 99.N	00001000
DO 9 IT=1+N	00001100
50 READ 110.ANAME.UL.LL.L.DL.DU.DD.AX.BX.CX.DX.AY.BY.CY.DY.AZ.BZ.CZ.	00001200
1 DZ	00001300
DELK=6.28318/L	00001400
E≖DELK/50•	00001500
9F1 KK=2+3E−5/L	00001600
12!=(DU-DL)/00+1.	00001700
DO 15 127=1+171	00001800
DDD=DL+CD+(1ZZ-1)	00001900
PRINT 160 ANAME OLL OLL	00002000
	0002000
PRINT 102-000	00002200
PRINT 101.E.DELK.DELKK	
00 1 1=1.2	00002300
w1=6943.	00002400
IF(I=EQ=2) W1=10600+	00002500
NX1=F[N(W)+1)	00002600
hyl=FIN(W1.2)	00002700
NZ:=F1N(w1+3)	00002800
₩2=LL	00002900
SO TO 11	00003000
10 w2=w2-w2/8.	00003100
IF(W2.LT.UL) GO TO 1	00003200
11 W3=1-/(1-/W1+1-/W2)	00003300
IF(W1.GT.LL.OR.W1.LT.UL.OR.W2.GT.LL.OR.W2.LT.UL.OR.W3.GT.LL.OR.W3	
	00003500
	00003600
NX2*FIN(W2+1)	00003700
NY2=FIN(WE+2)	00003800
NZ2*FIN(WZ+3)	
NX3=FIN(W3.1)	30003900
NY3=FIN(W3+2)	00004000
NZ3=FIN(W3.3)	00004100
DIV=DDD/((NX1+NZ1)/2+)	00004200
D=ASIN((W2/W3)*SIN(DIV +ASIN((W3/W2)*SIN(-DIV))))*C1	00004300
DO 4 K=1.6	00004400
1F(K.GT.3) GO TO 6	00004500
3 1N3=2	00004600
INI=1	00004700
1 N2 = 1	00004800
1F(K-EQ-2) IN1=2	00004900
1F(K+EQ+3) 11:2*2	00005000
GO TO 12	00005100
6 IN3=1	00005200
	00005300
IN1=2	00005400
1N2=2	
TRAM-EO.EN INLAL	
IF (K-EQ-5) INI=1	00005500
IF (K.EQ.6) 1N2=1	00005500 0000 5600
IF(K.EQ.6) 1N2=1 12 J=1	00005500 00005600 00005700
IF (K.EQ.6) 1N2=1	00005500 0000 560 0

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```
CALL HWDK(L+TCL+0+4)
1F(1X+GT+1) GO TO 5
                                                                           00006100
                                                                            00006200
   HWC1=HW1*C1
                                                                            00006300
   HWC2=HW2#C1
                                                                            00006400
   FN=FN2(TCL)
                                                                            00006500
   EXHW1=ASIN(SIN(HW1)#FN)#C1
   EXHW2=ASIN(SIN(HW2)#FN)#C1
                                                                            00006600
                                                                            00006700
   PC1=PVAR(TCL+0++D1V/2++0+)
   PC2=PVAR(TCL+0++-DIV/2++0+)
                                                                            00006800
                                                                            00006900
   CALL HWDK(L.TCL+D1V/2..PC1.6)
                                                                            00007000
   HWC3EHW2
   CALL HWDK(L+TCL-01V/2++PC2+5)
                                                                            00007100
   HWC4=HW1
                                                                            00007200
                                                                            00007300
   A1=DIV/2++A6S(PC1+HWC3)
                                                                            00007400
   A2=DIV/2++A8S(PC2+HWC4)
                                                                            00007500
   FN=FN2(TCL)
   EXWITABS(ASIN(SIN( A) )#FN)+ASIN(SIN( A2 )#FN))#C1
                                                                            00007600
                                                                            00007700
   HWC3=HWC3+C1
                                                                            00007800
   HWC4=HWC4+C1
                            main of the state of the same
                                                                            00007900
   FNL1=(A1+A2) #C1/D
                                                                            00008000
   DQ=0.
                                                                            00008100
 7 TNCL=TNCPM(TCL+DQ)
   CALL HWDK(L.TNCL.PNC.3)
                                                                            00008200
   HWNC1=HW1+C1
                                                                            00008360
                                                                            00008400
   HWNC2=HW2*C1
   FN#FN2 (TNCL+PNC)
                                                                            00008500
                                                                            00008600
   EXHWS=ASIN(SIN(HW1)#FN)#C1
                                                                            00008700
   EXHW6 = ASIN(5[N(HW2) +FN) +C1
    1F(J.EQ.2) GO TO 8
                                                                            00008800
                                                                            00008900
   CALL OUT
                                                                            00009000
    J=2
   DQ=DELK
                                                                            00009100
                                                                            00009200
   TCL=FNX(0++0++DQ)
    GO TO 7
                                                                            00009300
 8 PNC1=PVAR(TNCL.PNC.DIV.DELK)
                                                                            00009400
   CALL HWOK(L.TNCL+DIV.PNC1.3)
                                                                            00009500
                                                                            00009600
   HWNC3=HW1
                                                                            00009700
   HWNC4=HW2
   FN#FN2 (TNCL+PNC)
                                                                            00009800
    EXW2=ABS(ASIN(SIN(HWNC3)#FN)-ASIN(SIN(HWNC4)#FN))#C1
                                                                            00009900
    HWNC3*HWNC3*C1
                                                                            00010000
                                                                            00010100
   HWNC4#HWNC4#C1
                                                                            00010200
   FNL2=ABS(HWNC3-HWNC4)/D
                                                                            00010300
 E CALL OUT
                                                                            00010400
 4 CONTINUE
                                                                            00010500
 2 GO TO 10
                                                                            00010600
 1 CONTINUE
                                                                            00010700
15 CONTINUE
                                                                            00010800
 9 CONTINUE
                                                                            00010900
100 FORMAT(20X+21H+++ UP-CONVERSION IN +A5+4H +++//39H THE SHORTEST WA00011000
   IVELENGTH TRANSMITTED IS .FIO.2/38H THE LONGEST WAVELENGTH TRANSMITOOD11100
   2TED IS .FIO. 2/25H THE LENGTH OF CRYSTAL IS .FIO. 2. 2X. 3HCM. / 90H ALODOLIZOD
   BL PHASE MATCH ANGLES ARE IN DEGREES, P.M. ANGLES ARE MEASURED DETWO0011300 AEEN THE Z-AXIS AND KI /33H TCL . COLINEAR PHASE MATCH ANGLE /37H T00011400
   SNCL = NONCRITICAL PHASE MATCH ANGLE /49H PNC = ANGLE BETWEEN (K1.4K00011500
   62) FOR NONCRITICAL P.M. /36H ALL HALFWIDTHS ARE IN MILLIRADIANS / 00011600
   777H HWC . HALFWIDTH OF DELK VS. THETA CURVE MEASURED BETWEEN MAX. 00011700
   BAND FIRST ZERO/39H HWNC = HALFWIDTH FOR NONCRITICAL P.M. )
```

```
102 FORMATE 68H PC1.PC2 = PC1 FOR TCL = TCL+OR-DIV/2+ THE INTERNAL DIVOCO11900
   TERGENCE OF WI / 31H PNCI = PNC FOR TNCL = TNCL+DIV / 32H EW = EXTEGOO12000
   2RNAL ANGULAR APERATURE / 32H R = NUMBER OF RESOLVEABLE LINES / 349H EXTERNAL DIVERGENCE (FULL ANGLE) OF PUMP BEAM = .F6.4)
                                                                          00012100
101 FORMAT(46H HWC AND HWNC ARE MEASURED WITH TCL/TNCL FIXED /19H DELT00012300
   1A K IS WITHIN .F7.3.15H 1/CM. OF 2P1/L/9H 2P1/L # .F7.3.5X.24H (2P00012400
   21/L]/K3 IS APPROX = .E10.3/46H K1.K2. AND K3 ARE COPLANER IN THE (00012500
   34.Z) PLANE /37H E POLARIZATION IS IN THE (4.Z) PLANE /41H O POLARIGO012600
   AZATION IS OUT OF THE (Y.Z) PLANE /69H FOR UNIAXIAL CRYSTALS THE Z-00012700
   SAXIS . C-AXIS. NZ . NE. AND NX . NY . NO /26H + INDICATES DELTA K 00012800
   6: 2PI/L /56H W1.W2.W3 CORRESPOND TO PUMP. IR. AND SIGNAL WAVELENGTOOD12900
   7HS /55H NX.NY.NZ ARE REFRACTIVE INDICES FOR X.Y.Z OPTICAL AXIS //500013000
   A9H ALL POSSIBLE UP-CONVERSION PROCESSES ARE LISTED BELOW ----///)00013100
110 FORMAT(A5.5X.6F10.1/4F10.4/4F10.4/4F10.4)
                                                                          00013200
    END
                                                                           00013300
   FUNCTION THEPM(TCL+D)
                                                                           00013400
    COMMON /10/P
                                                                           00013500
                                                                           00013600
    T=TCL
    DP=0.05
                                                                           00013700
  5 T1=FNX(DP+3+14159+D)
                                                                           008E1000
                                                                           00013900
     IF(T1.LT.T) GO TO 10
                                                                           00014000
    DP=-DP
                                                                           00014100
    T1=FNX(DP+3+14159+D)
                                                                           00014200
    IF (TI.LT.T) GO TO 10
                                                                           00014300
    DP=DP/10.
    IF(ABS(DP)+LT+0+00001) GO TO 21
                                                                           00014400
                                                                           00014500
    GO TO 5
 10 T=T1
                                                                           00014600
                                                                           00014700
    PEOP
                                                                           00014800
 14 T1=FNX(P+DP+3+14159+D)
                                                                           00014900
    IF(T).LT.T) GO TO 12
                                                                           00015000
    P=P+DP
                                                                           00015160
    DP=-DP/4.
    IF (ABS(DP).LT.0.0001) GO TO 20
                                                                           00015200
                                                                           10015300
    GO TO 14
                                                                           J0015400
 12 P=P+DP
                                                                           00015500
                                                                           00015600
    T=T1
                                                                           00015700
    GO TO 14
 20 TNCPM=T1
                                                                           00015800
                                                                           00015900
    RETURN
 21 TNCPM=T1
                                                                           00016000
    PEDP
                                                                           00016100
    RETURN
                                                                           00016200
                                                                           00016300
    FND
    FUNCTION PVAR(T.P.DD.E)
                                                                           00016400
    COMMON/1/W1+W2+W3/2/K1
                                                                           00016500
                                                                           00016600
    REAL KI
    D= .001
                                                                           00016700
    1F(DD.GT.0.0) D=-D
                                                                           00016600
    PP±P
                                                                           00016900
    T1 = T+DD
                                                                           00017000
    K1=6.28318E8#FN1(T1)/W1
                                                                           00017100
  1 PP=PP+D
                                                                           00017200
  2 X1=ABS(FDK(T1+PP)+E)
                                                                           00017300
    x2=ABS(FDK(T1+PP+D)+E)
                                                                           00017400
                                                                           00017500
    IF ( x2+LT+x1 ) GO TO 1
    PP=PP+D
                                                                           00017600
    D=-D/5.0
                                                                           00017700
```

	1F(ABS(D)+LT+1E-5) GO TO 10	00017800
11	GO TO 2	00017900
	PVAR=PP	00018000
	RETURN	00018100
	END	00581000
	FUNCTION FNX(XX+PP+DD)	00018300
	DATA (E=1.E=6)	00018400
	COMMON/1/W1+W2+W3 /4/1JX	00018500
	FK(Q+A)=SQRT((FN1(A)/W1)++2+FN2C(Q)/(W2+W2)-2.*FN1(A)+	00018500
	. SUR! (FN2C(Q)) #CXX/(W1#W2))	00018700
	D=DD/6.28318E8	00018800
	P=PP	00018900
	X=XX	00019000
	IF(XX.GT.0) GO TO 20	00019100
	X=-X	00019200
	P=3+14159274+PP	00019200
20	IKX=IJX=0	00019400
	D1=ABS(XP-XX)	00019500
	XP=XX	00019600
	CX=COS(X)	00019700
	SX=SIN(X)	00019860
	CXX=COS(3.1415927-X)	00018800
	CP=COS(P)	0002000
	IF (R.LT.0.07.0R.R.GE.1.57) R=0.07	00020100
	IF(D1+LT+190+#E) D1=100+#E	70020200
	IF(D1+GT+0+1) D1=0+1	00020300
	IF(R+EQ+0+07) D1=0+1	999499
1	IKX=IKX+1	00040500
	1F(1KX+GT+100) GO TO 5	00020600
	RD=R+D1	00020700
	CR*COS(R)	0080500
	SR*SIN(R)	00020900
	CRD=COS(RD)	00021000
	SRD=SIN(RD)	00021100
	C2=CR+CX+SR+SX+CP	00021200
	C5*CRD*CX+SRD*SX*CP	00021300
	Y1=FK(C2+R)	000<1400
	Y2=FK(C5+RD)	00021500
	C3=(FN1(R)/W1-CXX#SQRT(FN2C(C2))/W2)/Y1	00021600
	C4=(FN1(RD)/W1-CXX+SQRT(FN2C(C5))/W2)/Y2	00021700
	C6=C3+CR+SR*SQRT(ABS(1C3+C3))*CP	00021800
	C7=C4+CRD+SRD+SQRT(ABS(1,-C4+C4))+CP	00021900
	Y=ABS(SQRT(FN3C(C6))/W3+D-Y1)	00022000
	Z=ABS(SQRT(FN3C(C7))/W3+D-Y2)	00022100
	IF (ABS(DI)+LT+ E) GO TO 2	000<2400
	IF (IKX+EQ+1) GO TO 10	00022300
	IF (Y•GT•Z) GQ TQ 3 D1≈-D1/10	00022400
	R=R-10#D1	00022500
	GO TO 1	00022600
7	RER+D1	00022700
3		000≤2800
	IF (R.LT.0.0.0.OR.R.GE.1.6) GO TO 12	00045400
2	FNX=R	00023000
-	IF(C6.LT.0.) [JX=2	00023100
	RETURN	00023200
10	IF(Z+GT+Y) D1=-D1	00023300
	IF (Z*GT*Y) GO TO 1	00023400
	60 TO 3	00023500
	·	000£3600

R. A. ANDREWS

		000
	1F(iJX.GT.0) GO TO 6	00043700
14	1JX=1	00053800
	R=0.07	0002. 100
	D1*0*i	0002000
	IKX=1	00024100
	GO TO 1	00024200
6	17X=S	00024300
	R=0.0	00024400
	RETURN	00024500
5	IF(IJX.GT.O) GO TO B	00044600
	GO TO 14	00024700
a	PRINT 1444X+P+R	00024800
	IJX=2	00024900
	FNX=R	00025000
144	FORMAT(10H FNX ERROR +5X+3HX = +F9+4+5X+3HP = +F9+4+5X+3HR	-179.4)00025100
	RETURN	00045400
	END	00025300
	FUNCTION FDK(T+P)	00045400
	COMMON /1/W1.W2.W3/2/K1	00025500
	REAL K2+K2S+K2C+K3+K1	00025600
	DATA (C1=6.28318E8)	00025700 00025800
	K2=C1+FN2(T+P)/W2	00025000
	K2S=K2*S1N(P)	00025900
	K2C=K2+COS(P) P3=ATAN(K2S/(K1+K2C))	00059100
	K3=C1+FN3(T+P3)/W3	00026200
		00026300
	FDK=K3-SQRT(K2S**2+(K2C+K1)**2)	00026400
	RETURN :	00026500
	SUBROUTINE HWDK(L,T,P+1)	00026600
	REAL L.L2.K1	00046700
	DATA (CC=6,28318E8)	000<6800
	COMMON /1/W1 · W2 · W3 /2/K1/5/V1 · V2 · E/4/1X	00046900
	KI=CC#FN1(T)/WI	00047000
	L2= 6.28318/L	00027100
	IF(ABS(FDK(T.P)).GT.L2*1.5) GO TO 30	90027200
	DV=0.01	00027300
	IF(1.EQ.2.OR.1.EQ.6) DV=01	00027400
1	V*DV	000∠7500
2	DK*FDK(T+P+V)	00047600
	IF(1.GT.3) DK=ABS(DK)	00047700
	IF(ABS(DK -L2).LT.E) GO TO 20	00047800
	IF(DK .LT.L2) GO TO 10	00027900
	DV=DV/10.	00028000
	IF(ABS(DV).LT.1E-6) GO TO 31	00058100
	V=V=DV#9*	00028200
	GO TO 2	00048300
10	V=V+DV	00028400
	GO TO 2	00048500
20	IF(DV.LT.0.) GO TO 25	00048600
	DV=-0+01	00028700
	V1=V	00028800
	IF(1.EQ(1.0R.1.EQ.5) GO TO 25	00058400
_	GO TO 1	00029000
25	V2=V	00029100
	RETURN	00029200
30	1 14 - 6	いりかいにいく
	1X=2	00029300
	1X=2 PRINT 100+T+P+L2 FORMAT(3F15+5)	00029300 00029400 00029500

	RETURN END	000<9600
	SUBROUTINE OUT	00029700
		00059800
		00049900
	1/11/K+TC+TNC+HW1+HW2+HWN1+HWN2+HW3+HW4+HWN3+HWN4+UU+J+UV	00004000
	2/12/EHW1+EHW2+EXW1+EXW2+EHW5+EHW6+FNL1+FNL2+PCL1+PNLL1+PCL2 3	00070100
	- For the first the first transfer to the first transfer transfer to the first transfer tran	00030400
	REAL NX1.NX2.NX3.NY1.NY2.NY3.NZ1.NZ2.NZ3	00030300
	DATA (UP=57,2957795) (ON=,017453293)	00030400
	IF(K+GT+1+OR+J+GT+1) GO TO 5	00010500
	DIV=DV+1000.	0000000
	VICTURE EXPENSE I SUPERIOR OF THE PROPERTY OF	000-0700
5	1F((IX•GT•1) GO TÜ 10 TCL=TC*∪P	00020800
	PC1=PCL1#UP	000-0900
	PC2=PCL2#UP	00031100
	TNGL = TNC+UP	
	PNC=PN*UP	00031300
	PNC1=PNCL1*UP	00031300
	IF (J.EQ.2) GO TO 3	00031400
	GO TO (11.12.13.14.15.16).K	00031900
1.1	PRINT 110.TCL.+HW1.+HW2.EHW1.EHW2.TNCL.PNC.+HWN1.+HWNZ.EHW5.EHW6	00031000
• •	RETURN	00816000
12	PRINT 120.TCL.HW1.HW2.EHW1.EHW2.TNCL.PNC.HWN1.HWN2.EHW5.EHW6	00071700
•-	RETURN	00002000
13	PRINT 130.TCL.HW1.HW2.EHW1.EHW2.TNCL.PNC.HWN1.HWN2.EHW5.EHW6	20034100
-	RETURN	00032200
14	PRINT 140.TCL.HW1.HW2.EHW1.EHW2.TNCL.PNC.HWN1.HWNZ.EHW5.EHW6	00035300
	RETURN	00032400
15	PRINT 150.TCL.HW1,HW2.EHW1.EHW2.TNCL.PNC.HWN1.HWN2.EHW5.CHWG	00032500
	RETURN	00032600
16	PRINT 160.TCL.HWI.HWZ.EHWI.EHWZ.TNCL.PNC.HWNI.HWNZ.EHWS.EHWS	00032700
	RETURN	00032800
10	GO TO (21,22,23,24,25,26),K	00032900
21	PRINT 2:0	00033000
	RETURN	00033100
22	PRINT 220	00033200
	RETURN	00023300
23	PRINT 230	00043400
	RETURN	00033500
24	PRINT 240	00043600
	RETURN	00011700
25	PRINT 250	00033800
	RETURN	00073400
26	PRINT 260	00034000
	RETURN	00034100
3	PRINT 170. TNCL.PNC.HWN1.HWN2.EHW5.EHW6	00034200
	PRINT 200.PC1.PC2.HW3.HW4.EXW1.FNL1.PNC1.HKN3.HWN4.EXW2.FNL2	00034300
	1F(K+EQ+6) GO TO 4	00034400
	RETURN	00034500
4	PRINT 300	00034600
	RETURN	00034700
	FORMATION WI = +F10+2+10x+5HWZ = +F10+2+10x+5HW3 = +F10+2+10x/3/6	
	1 NX = 4F104449X)/3(6H NY = 4F104449X)/3(6H NZ = 4F104449X)//	00034900
	25%, 35HINTERNAL RESOLUTION LIMIT (MRAD) = .F7.4.	00035000
	3 5X+ 16H1NTERNAL DIV. = +F6+4//)	00035100
	FORMAT(9H 0+0=E+7H TCL = + F7.4+2X+6HHWC = +4F6+1+2X+7HTNCL = F7.4+2X+6HPNC = + F7.4+2X+7HHWNC = +4F6+1)	
	FORMAT(9M E+0=E+7H TCL = + F7.4+2X+6HHWC = +4F6+1+2X+7HTNCL =	00035300
. 20	- Committee Front Fill ALV STORME - FALDSTREET	• VUUUD 7400

V MARKET PARTY OF THE PARTY OF

```
F7.4:2X:6HPNC #
                             F7-4.2x.7HHWNC = .4F6.1)
                                                                          00035500
130 FORMAT(9H 0+E=E---- 7H TCL = + F7.4.2X.6HHWC = .4F6.1.2X.7HTNCL = +C0025000
          F7.4.2X.6HPNC = F7.4.2X.7HHWNC = .4F6.1)
                                                                          00035700
140 FORMAT(9M E+E=0----7M TCL = + F7 4 2X-5HHWC = +4F6+1+2X+7HTNCL =
                                                                         .00035600
          F7.4.2X.6HPNC = . F7.4.2X.7HHWNC = .4F6.1)
                                                                          00035900
150 FORMAT(9H 0+E=0----7H TCL & . F7:5.2X.6H WC = .4F6.1.2X.7HTNCL =
                                                                        400046000
          F7.4.2X.6HPNC = . F7.4.2X.7HHWNC = .4F6.1)
                                                                          00036100
160 FORMAT(9H E+0=0----7H TCL = + F7+4+2X 6HHWC = +4F6+1+2X+7HTNCL = +00036400
          F7.4.2X.6HPNC = . F7.4.3X.75 HWNC : .4F6.1)
                                                                          00036300
170 FORMAT(9H
                  *
                         4.24
                                                                7HTNCL = .00036400
          F7.4.24 GHENC . F7.1.2X.7HHWNC . .4F6.1)
                                                                          00036500
200 FORMA' (10x+5MPC1 =+#7+4+6M PC2 =+F +4+5H HW #+2F6+1+4H EW#+F6+1+
                                                                          00036600
       3H Rt F5.1-7H PNG1 *+F7.4:5H HW *+2F6.1:4H EW*+F6.1:3H R=+F6.1)00036700
   1
210 / ORMAT(9H 0+0=E---,17(,28H*** NOT PHASE MATCHABLE ***
220 FORMAT(9H E+0=E---,10x,28H*** NOT PHASE MATCHABLE ***
                                                              )
                                                                          00036800
                                                                          00036900
230 FORMAT(9H O+E=E---+10X+28H### NOT PHASE MATCHAULE ###
                                                                           00037000
240 FORMAT(9H E+E=0---+10X+28H### NOT PHASE MATCHABLE ###
                                                              )
                                                                           00037100
250 FORMAT(9H 0+E=0---+10X+28H### NOT P' #5E MATCHAULE ###
                                                                           00027400
260 FORMAT(9H E+0=C----10x+28H*** NOT P ASE MATCHABLE *** //39(3H *)00037300
         111
                                                                           00037400
309 FORMAT (//30(3H #1//)
                                                                           00037500
    ENO
                                                                           00037600
    FUNCTION FIN(Wal)
                                                                           00057700
    COMMON/13/AX. BX. CX. DX. AY. BY. CY. DY. AZ. BZ. CZ. DZ
                                                                           00037800
                                                                           00027900
    X=W#W#1.0E-8
                                                                           00038000
    GO TO (1.2.3) . I
  1 FIN=SQRT(AX+BX/(X-CX)-DX#X
                                                                           00038100
    RETURN
                                                                           00038200
  2 FIN=SQRT(AY+BY/(X-CY)-DY#X)
                                                                           00038300
                                                                           00038400
    RETURN
  3 FINESOR / (AZ+BZ/(X-CZ)-63%+X)
                                                                           00028500
                                                                           00028600
    RETURN
                                                                           00038700
    END
                                                                           00026400
    FUNCTION FN1(A)
    COMMON /1/W1.W2.W3
                                           /9/IN1
                                                                           00038900
      /6/NX1.NX2.NX3.NY1.NY2.NY3.NZ1.NZ2.NZ3
                                                                           00039000
                                                                           00039100
    REAL NX1.NX2.NX3.NY1.NY2.NY3.NZ1.NZ2.NZ3
    GO TO (1.2).IN1
                                                                           00039200
    FN1=NX1
                                                                           00039300
                                                                           00039400
    RETURN
  2 FN1=1./SQRT((CQS(A)/NY1) ##2+(SIN(A)/NZ1)##2)
                                                                           00039500
                                                                           00039600
    RETURN
                                                                           00039700
    END
                                                                           00029800
    FUNCTION FN2(A)
    COMMON /1/W1.W2.W3/8/IN2
                                                                           00039900
       /6/NX1.NX2.NX3.NY1.NY2.NY3.NZ1.NZ2.NZ3
                                                                           00040000
                                                                           00040100
    REAL NX1 1XX2 NX3 NY1 NY2 NY3 NZ1 1NZZ NZ3
    GO TO (1.2: . IN2
                                                                           00040200
                                                                           00040300
  1 FN2sNX2
                                                                           00040400
    RETURN
  2 FN2=1./SQRT((CQS(A)/NY2)##2+(SIN(A)/NZ2)##2)
                                                                           00040500
                                                                           00045600
    RETURN
                                                                           00040700
    END
                                                                           00040500
    FUNCTION FN3(A)
    COMMON /1/W1+W2+W3/7/IN3
                                                                           00040900
    EZM. SZM. I ZM. CYM. GYM. I YM. EXM. SXM. I XM. 6\
                                                                           00041000
    REAL NXI-NX2+NX3+NYI+NY2+NY3+NZI+NZZ+NZ3
                                                                           00041100
    GO TO (1.2) . IN3
                                                                           00041200
                                                                           00041300
  1 FN3*NX3
```

RETURN	00041400
2 FN3=1./5QRT((COS(A)/NY3)##2+(SIN(A)/NZ3)##2)	00011500
RETURN	00041600
END	00041700
FUNCTION FN2C(Q)	00041800
COMMON /1/W1 . W2 . W3/8/1N2	00041900
4 /6/NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3	00042000
REAL NX1 NX2 NX3 NY1 NY2 NY3 NZ1 NZ2 NZ3	00042100
GO TO (1.2). IN2	00042200
1 FN2C=NX2+NX2	00042300
RETURN	00042400
2 FN2C=1./((Q/NY2)**2+(1Q*Q)/NZ2**2)	00042500
RETURN	00042600
END	00042700
FUNCTION FN3C(Q)	00042800
COMMON /1/W1.W2.W3/7/IN3	00042900
4 /6/NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3	00043000
REAL NX1 NX2 NX3 NY1 NY2 NY3 NZ1 NZ2 NZ3	00043100
GO TO (1.2).1N3	00043200
•	00043300
1 FN3C=NX3*NX3	00043400
RETURN	00043500
2 FN3C=1./((Q/NY3)##2+(1G#0)/NZ3##2)	
RETURN	00043600
FNC.	00043700

Appendix B
SAMPLE INPUT DATA AND PROGRAM OUTPUT

90

00	
1.0 .00192511 .00192511	
135000. 135665 135665 138793	
6300. •36579 •36579	
HGS 6.9445 6.9445 8.39218	

THE SHERTEST KAVELENGIH TKAMSPITTED IS — K3FO.00 THE LENGEST VAVELENGIH TKAMSPITTED IS 1.45AAA.00 THE IFACTH FF CHYSTAL IS — 1.60 CM. ALL PHASE FJTCH ANGLES ANE IN DEGMEES, P.M. AMGLES ARF MEASURED BETWEFN THE Z-AXIS AND K1 SHERTEST KAVELENGTH TKANSMITTED 15 63F0.00 LENGEST VAVELEASTH THANSMITTED 15 135000.00 ICL = CELLT : AP PHESE PATCH APCLE

BOO LIP-CERVENSIEN IN MES

INCL = NEWCRITECAL PHASE MATCH ANGLE
PNC = ANGLE SCIWER (FIJKZ) FMF NOWCRITCAL P.M.
ALL FALFWINTS AME IN MILLIFALIANS
MNC = MATFWINTH OF DELM VS. IMPTA CURVE MEASURED PETMEES FAX. AND FIRST ZFROMENC = FALFFINTH OF NOWCHITCAL P.M.

PC1.PC2 = PC1 FEE 1CL = 1CL+6F-GIV/2, THE INTERNAL DIVENGENCE OF M1 PNC1 = PUG FOR INCL = IACL+6IV

R = NUMPER OF RESELLABLE LINES EXTERIAL PLYFFGENCE (FULL ANGLE) OF PUMP PFAM = 0.0010 MMC ARE HARE ARE PERSCHED WITH TOLITINGL FIXED EN F FYTERRAL AMBLLAM AFFLICHE

0.126 1/[h. 6F 2P|/!. KINKS, AND KE ARE CHPLA AM IN THE (YAZ) PLAME DELLA K 15 PITHIN 2PI/L = 6,273

FOR UNIANIAL CRYSTALS THE Z-AXIS & C-AXIS, 72 & NE. AND NX # PHEARTZATTER IS ELT HE THE (Y,Z) PLANE PELANIZATIEN 'S IN THE (Y.Z.) PLANE

MI, WZ, KI CERRESPONE IN PURP. IR, AND SIGNAL MAYELFNGINS KX,NY,NZ ARE REFRACTIVE INDICES FOR X,Y,Z FUTICAL AXIS . INDICATES FELTA K = 2017L

BK . Az

ALL PASSIPLE UP-CFAVEPSIME PROCESSES ARE LISTED BELOK ----

		18.6 18.0 18.4 17.1
		40, 5 - 40
		19. 19. 19. 19. 19. 19. 19. 19. 19. 19.
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		2.20 2.40 2.00 2.00 2.00 2.00 2.00 2.00
		# 10 # # # # # # # # # # # # # # # # # #
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6565.39 2.6566 2.6566 3.1944	ā.	"" "" " " " " " " " " " " " " " " " "
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135000+00 2.5687 2.5687 2.5687	3	# # # # # # # # # # # # # # # # # # #
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PROCESSES IN NONLINEAR CRYSTALS				
4. DESCRIPTIVE NOTES (Type of report and inclusive deles) This is an interim report; work on the pro	hlam is continu	ina		
5. AUTHOR(8) (Figst name, middle initial, last name)	otem is continu	mg.		
R.A. Andrews				
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to determine (a) the range of IR wavelengt process, (b) the PM orientation of the wav	ns that can be c e vectors for ci	onverted in citical and no	a phase matched (Pi oncritical PM. (c) th	NI) Le
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Security Classification

S/N 0101-807-6801

Winnell &

- Cower's Single (**Jening)** (1975) - Alphin (1985) -

Security Classification ROLE WT ROLE WT ROLE WT Optical parametric processes Up-Conversion Nonlinear crystals Quantum optics

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